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THE ORDER OF CRYSTALLIZATION IN IGNEOUS ROCKS

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A recent paper in this journal by Mr. Victor Ziegler[1] takes the form of a criticism of a paper by Bowen on the order of crystallization in igneous rocks.

Ziegler does not question the statement of Bowen that "the observation of all the relations of outline of a number of minerals in a section of a holocrystalline granular rock leads to a safe conclusion only as to the order in which the minerals have ceased to crystallize." The fact that there is agreement on this point is worth noting.

Ziegler does, however, believe that this order of cessation of crystallization must be also the order of beginning of crystallization. He says, "the order of cessation of crystallization gives a definite clue to the order of beginning of crystallization," although he himself has discussed the crystallization of three-component metal systems in which the final crystallization always consists in the simultaneous formation of three solid phases (simultaneous cessation of crystallization), whatever difference there may be in the order of beginning of crystallization which varies with the relative proportions. Clearly in those systems the cessation of crystallization gives no clue to the beginning.

Bowen in the original paper clearly recognized that if the crystallization of a rock magma is analogous to that of the simple chemical systems that have been studied, the final crystallization should consist in the formation of a number of solid phases (polycomponent eutectic) and that there would be no *order* of cessation of crystallization. It was suggested that the complications which follow from the prevalence of solid solutions among the components of rock magmas might, however, give a result which need not be analogous to simple systems. Ziegler discusses two three-component systems in which there is no solid solution and points out that "there is no recurrence of the substance first crystallized in either case. If substances are capable of forming solid solutions they do not affect the above in any way." Yet Vogt,[1] following Schreinemakers has shown beyond doubt that, even in relatively simple systems, solid solution may bring about precisely the result denied it by Ziegler, viz. recurrent crystallization.

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[1] *Jour. Geol.*, XXI, 1913, p. 181.

In many respects it is entirely unsafe to fall back on analogy with simple systems. The average igneous rock is far from a simple system, neither was it formed under simple conditions. In the finally crystallized product important quantities of borates, fluorides, chlorides, water, CO_2, etc., are not represented. The early portion of the crystallization of a rock magma (the beginning of crystallization) is undoubtedly due chiefly to the cooling-down of the magma, whereas the addition of the final layers to the crystals (cessation of crystallization) may be, *in part*, due to a process which approaches an evaporation during which the above volatile substances are removed. The complications are such that it is entirely unsafe to extrapolate from simple systems investigated under simple conditions.

For this reason Bowen, in the original paper, avoided theoretical discussion, since it must necessarily be on the basis of such extrapolation, and turned to the evidence of the rocks themselves. Thus, certain conclusions were arrived at concerning the order of beginning of crystallization based on the consideration of volcanic rocks as the quenched equivalents of plutonic rocks. Ziegler doubts whether this method is justifiable and points out that the difference of conditions under which volcanic and plutonic rocks crystallize, taking the specific cases of granite and rhyolite, might, theoretically, bring about a different order of crystallization. Certainly, if theoretical considerations were all the light on the subject available, the question would have to remain in this condition of doubt, but there exists other evidence. In nature, rocks occur which have been formed under every conceivable gradation of conditions intermediate between those characteristic of the formation of granite and of rhyolite. The rocks formed under these intermediate conditions confirm the evidence of the rhyolites as to the order of beginning of crystallization as Bowen has pointed out. There is not only no evidence that the difference of conditions brings about a reversal in order of crystallization but there is definite positive evidence that no such drastic change occurs.

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[1] *T.M.P.M.*, XXVII, 141–55.

In view of the fact that the objections of Ziegler are almost entirely the outcome of theoretical considerations which it is dangerous to extend to such complicated systems, and that the evidence of the rocks themselves, on which Bowen based his conclusions, is not questioned, it does not appear that the objections offered seriously impair the conclusions reached by Bowen.

A knowledge of the order of beginning of crystallization is important for the elucidation of the differentiation of rock magmas. Differentiation is not uncommonly discussed in terms of the assumption that ferromagnesian minerals are minerals of early crystallization whether they are present to the extent of 70 per cent or of only 5 per cent. This assumption is often quite obviously at variance with the evidence of the porphyritic facies of the rock types described, and in such cases leads, of course, to erroneous conclusions.